

# **Search for Partonic EoS in High-Energy Nuclear Collisions**

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**Many Thanks to Organizers!**

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# Outline

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- **Motivation**
- **Bulk properties -  $\partial P_{QCD}$** 
  - Hadron spectra,  $v_2$ : partonic collectivity
  - NQ-scaling: deconfinement
  - Heavy flavor: thermalization
- **Summary & Outlook**

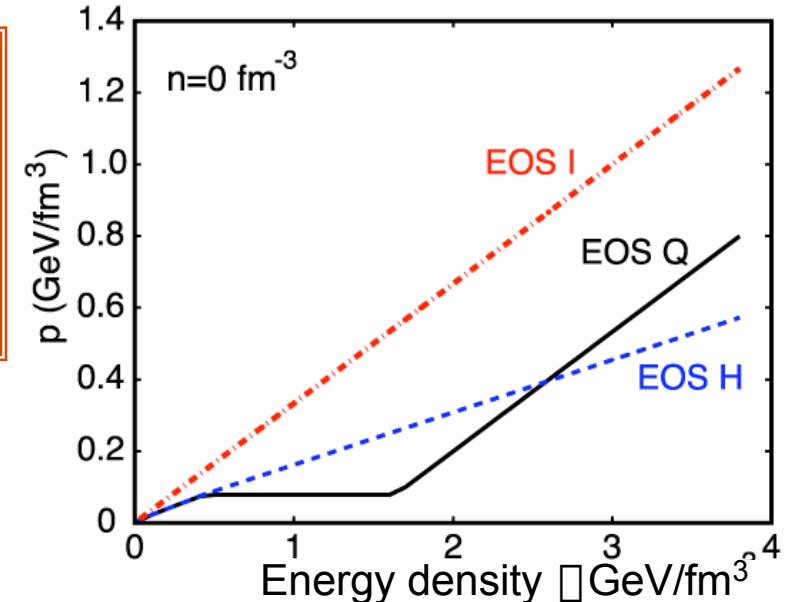


# Equation of State

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$\partial_{\mu} j^{\mu} = 0 \quad j^{\mu}(x) = n(x) u^{\mu}(x)$$

$$T^{\mu\nu} = [u^{\mu} + p(x)] u^{\nu} - g^{\mu\nu} p(x)$$



With given degrees of freedom, the EOS - the system response to the changes of the thermal condition - is fixed by its  **$p$**  and  **$T$**  ( $\Box$ ).

Equation of state:

- **EOS I**: relativistic ideal gas:  $p = \rho/3$
- **EOS H**: resonance gas:  $p \sim \rho/6$
- **EOS Q**: Maxwell construction:  
 $T_{\text{crit}} = 165 \text{ MeV}$ ,  $B^{1/4} = 0.23 \text{ GeV}$   
 $\rho_{\text{lat}} = 1.15 \text{ GeV/fm}^3$

*P. Kolb et al., Phys. Rev. **C62**, 054909 (2000).*

# Pressure, Flow, ...

$$\boxed{dS} = dU + pdV$$

$\square$ - entropy;  $p$  – pressure;  $U$  – energy;  $V$  – volume  
 $\square = k_B T$ , thermal energy per dof

In high-energy nuclear collisions, *interaction* among constituents and *density distribution* will lead to:

***pressure gradient*  $\square$  *collective flow***

- $\square$  number of degrees of freedom (dof)
- $\square$  Equation of State (EoS)
- $\square$  No thermalization is needed – pressure gradient only depends on the ***density gradient and interactions***.
- $\square$  Space-time-momentum correlations!



//Talk/2005/02icpaqgp05//



# Collectivity, Local thermalization

Hydrodynamic  
Flow

=

Collectivity

Local  
Thermalization



# High-Energy Nuclear Collisions

## Initial Condition

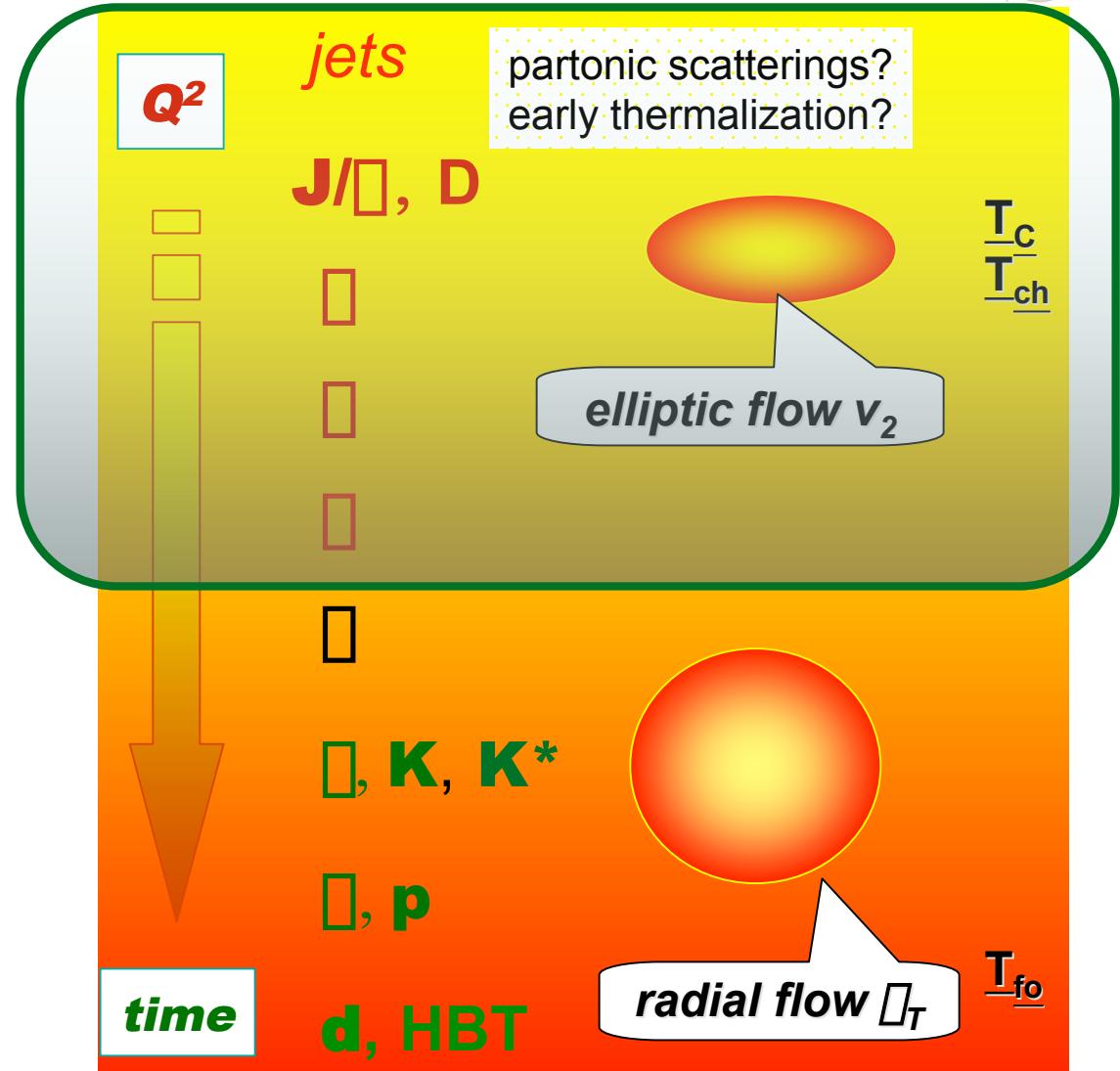
- initial scatterings
- baryon transfer
- $E_T$  production
- parton dof

## System Evolves

- parton interaction
- parton/hadron expansion

## Bulk Freeze-out

- hadron dof
- interactions stop





# Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\eta} = \frac{1}{2\pi} \frac{dN}{p_t dp_t dy} \left[ 1 + \sum_{i=1}^{\infty} 2v_i \cos(i\eta) \right]$$

$$p_t = \sqrt{p_x^2 + p_y^2}, \quad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass:

- Directed flow ( $v_1$ ) – early
- Elliptic flow ( $v_2$ ) – early
- Radial flow – integrated over whole evolution

Note on collectivity:

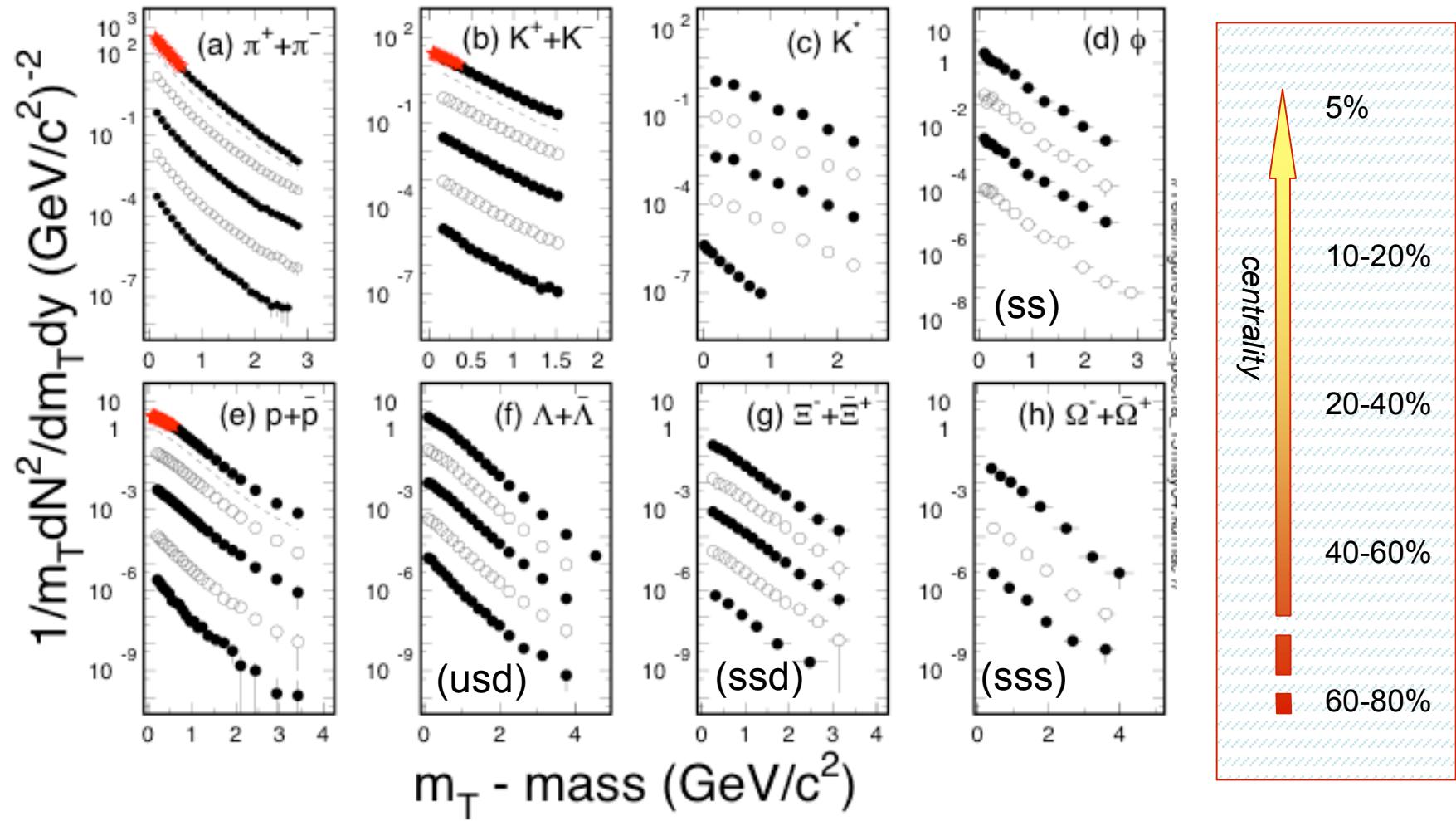
- 1) Effect of collectivity is accumulative.
- 2) Thermalization is not needed to develop collectivity - pressure gradient depends on ***density gradient*** and ***interactions***.



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# Hadron Spectra from RHIC

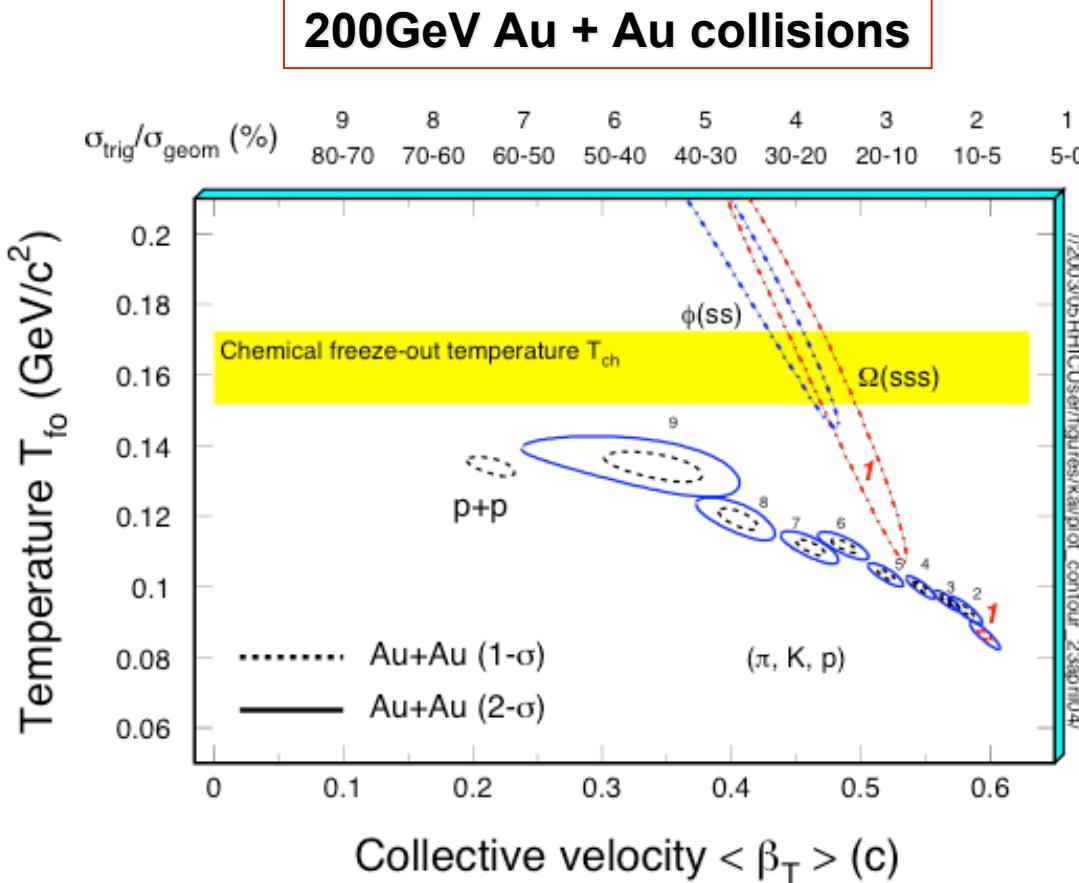
mid-rapidity,  $p+p$  and  $Au+Au$  collisions at 200 GeV



$$m_T = \sqrt{p_T^2 + m^2}$$

BRAHMS, PHENIX, and STAR experiments

# Thermal fits: $T_{fo}$ vs. $\langle \bar{K}_T \rangle$



Chemical Freeze-out:

Kinetic Freeze-out:

Single freeze-out:

Baran, Broniowski, Florkowski, Acta Phys. Polon. **B35**, 779(2004).

inelastic interactions stop  
elastic interactions stop

- 1) ( $\bar{K}_T$ ,  $K$ ,  $p$ ) contours change smoothly from peripheral to central collisions. Decay effects negligible.
  - 2) In top 5% most central collisions,  $\langle \bar{K}_T \rangle \sim 0.6c$ !
  - 3) Multi-strange particles ( $\bar{K}_T$ ,  $\bar{L}_T$ ) are found at higher  $T_{fo}$  ( $\sim T_{ch}$ ) and lower  $\langle \bar{K}_T \rangle$ .
- => Sensitive to early partonic stage**

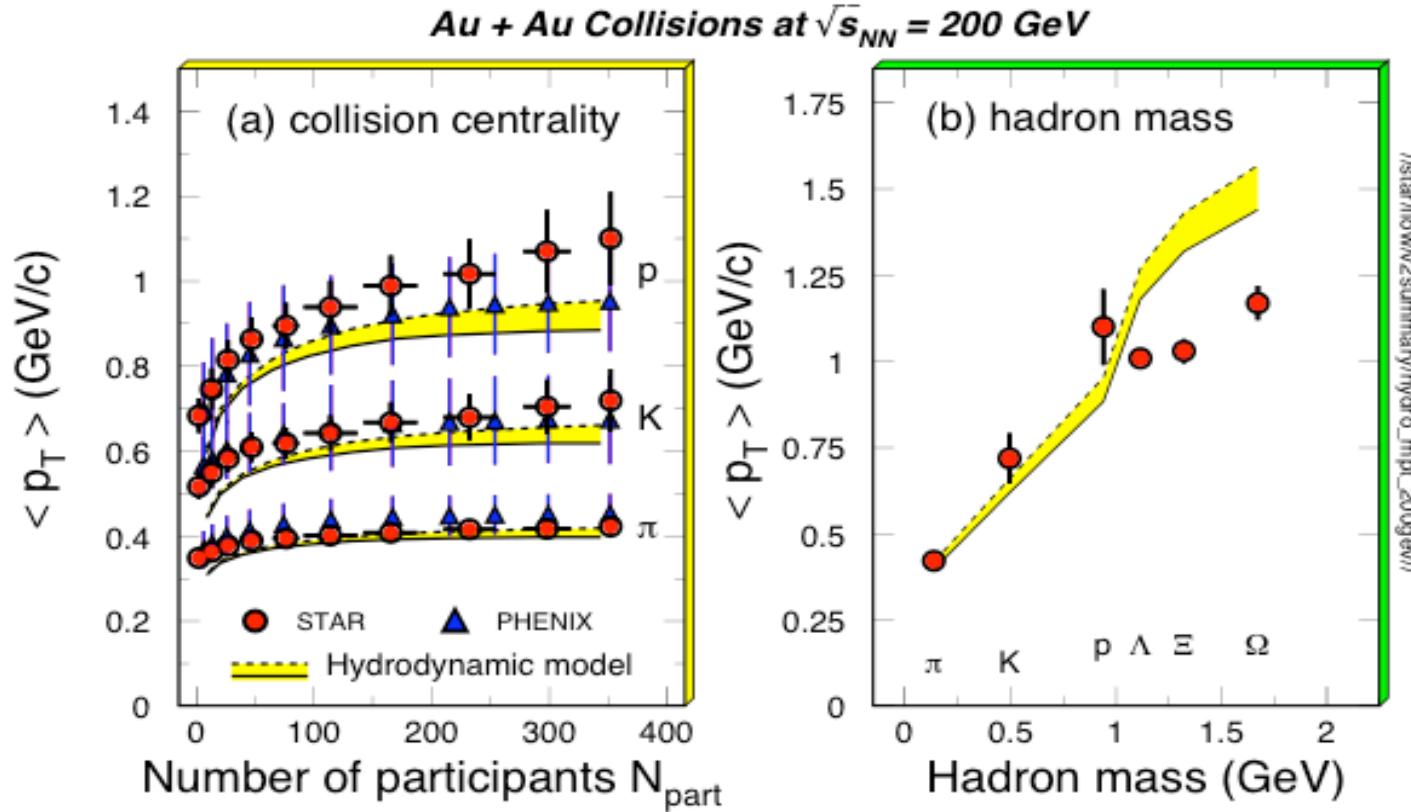
Data: STAR: NP**A715**, 458c(03); *PRL* **92**, 112301(04); **92**, 182301(04).

NA49: *nucl-ex/0409004*

Chemical fit: Braun-Munzinger, Redlich, Stachel, *nucl-th/0304013*

Thermal fit: Schnedermann, Sollfrank, Heinz, *PRC**48***, 2462(1993)

# Compare with Hydro Results



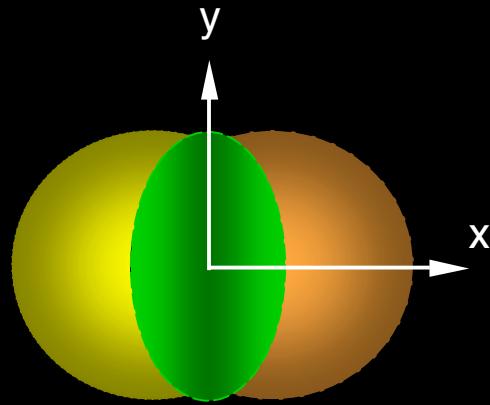
Model results fit to  $\pi$ ,  $K$ ,  $p$  spectra well, but over predicted  $\langle p_T \rangle$  for multi-strange hadrons - **Multi-strange hadrons do freeze-out earlier!**

*Phys. Rev. C69* 034909 (04); *Phys. Rev. Lett.* **92**, 112301(04); **92**, 182301(04); *P. Kolb et al., Phys. Rev. C67* 044903(03)

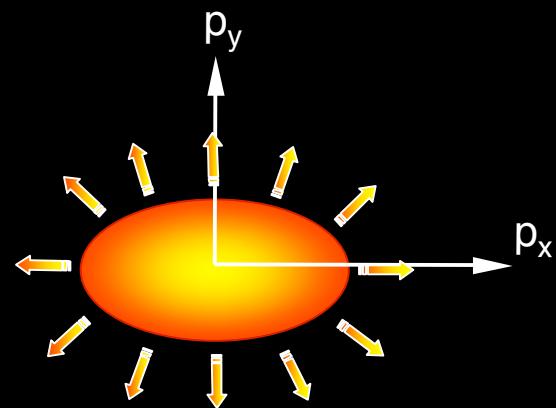


# Anisotropy Parameter $v_2$

coordinate-space-anisotropy



momentum-space-anisotropy

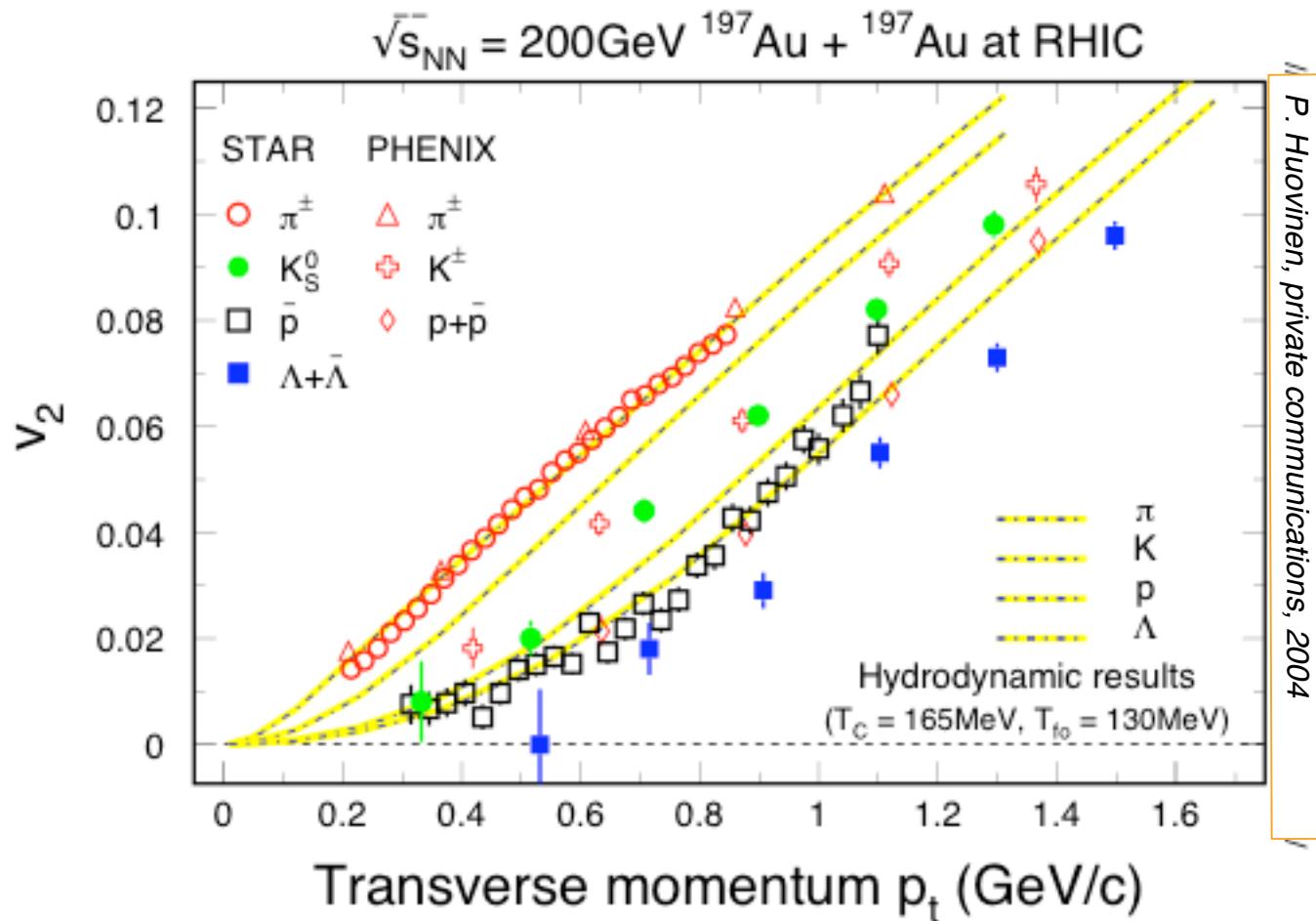


$$\square = \frac{y^2 - x^2}{y^2 + x^2}$$

$$v_2 = \langle \cos 2\square \rangle, \quad \square = \tan^{-1} \left( \frac{p_y}{p_x} \right)$$

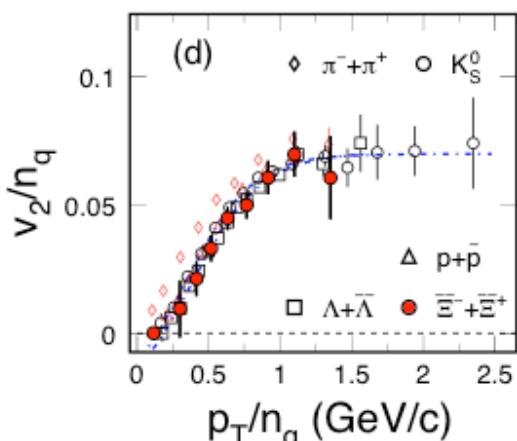
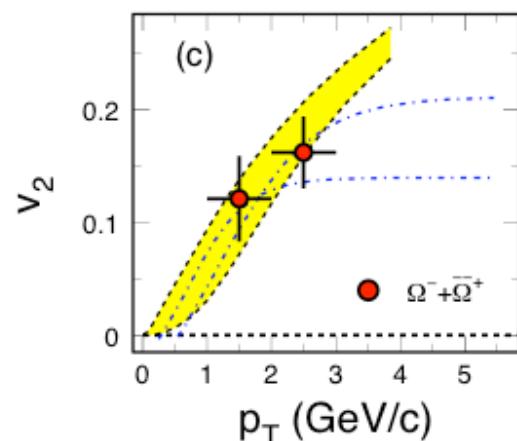
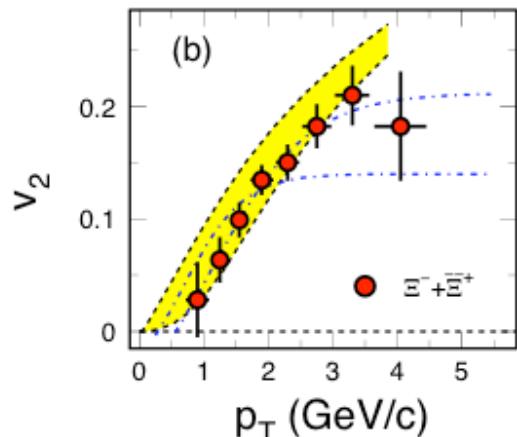
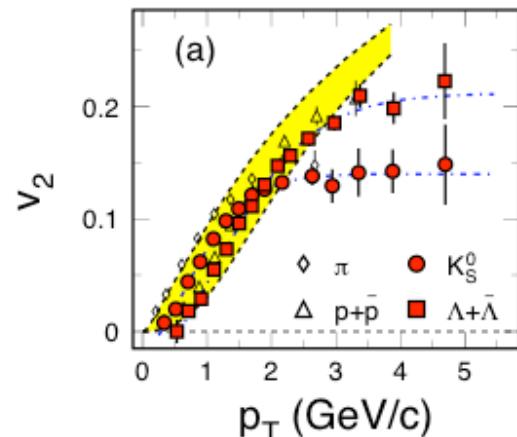
Initial/final conditions, EoS, degrees of freedom

# $v_2$ at low $p_T$ region



- Minimum bias data! At low  $p_T$ , model result fits mass hierarchy well!
- Details does not work, need more flow in the model!

# Full $p_T$ Results



- $v_2$ , spectra of light hadrons and multi-strange hadrons
- scaling of the number of quarks

At RHIC:

- ⇒ **Partonic collectivity**
- ⇒ **Deconfinement**

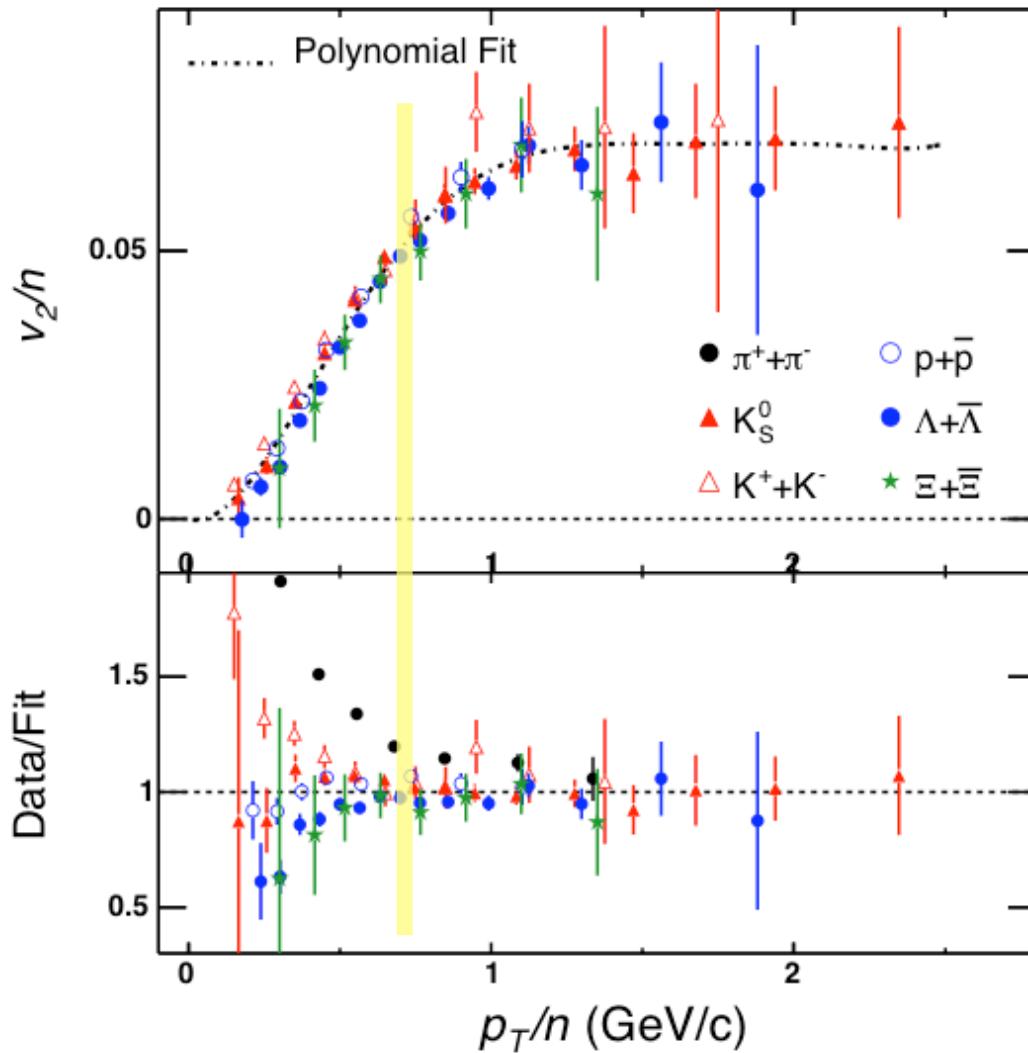
**PHENIX:** *PRL* **91**, 182301(03)  
**STAR:** *PRL* **92**, 052302(04)

S. Voloshin, *NPA* **715**, 379c(03)  
 Models: Greco et al, *PRC* **68**, 034904(03)  
 X. Dong, et al., *Phys. Lett.* **B597**, 328(04).  
 ....

**200GeV Au + Au minimum bias collisions**

# More on NCQ scaling

-- for P. Braun-Munzinger



## Au + Au at 200 GeV

- Minimum bias data set ( $\square_{\text{trig}}/\square_{\text{total}} \sim 0-80\%$ )
- NCQ-scaling works at  $p_T/n \geq 0.7$  GeV/c  $\square$   
Partonic collectivity !
- Below  $p_T/n \sim 0.7$  GeV/c, hadron mass dependent  $\square$   
hydrodynamic type flow with both partonic and hadronic collectivities



# Partonic Collectivity at RHIC

1) Copiously produced hadrons freeze-out:

$$T_{fo} = 100 \text{ MeV}, \quad \langle \bar{\ell}_T \rangle = 0.6 \text{ (c)} > \langle \bar{\ell}_T \rangle \text{ (SPS)}$$

2)\* Multi-strange hadrons freeze-out:

$$T_{fo} = 160-170 \text{ MeV } (\sim T_{ch}), \quad \langle \bar{\ell}_T \rangle = 0.4 \text{ (c)}$$

3)\*\* Multi-strange  $v_2$ :

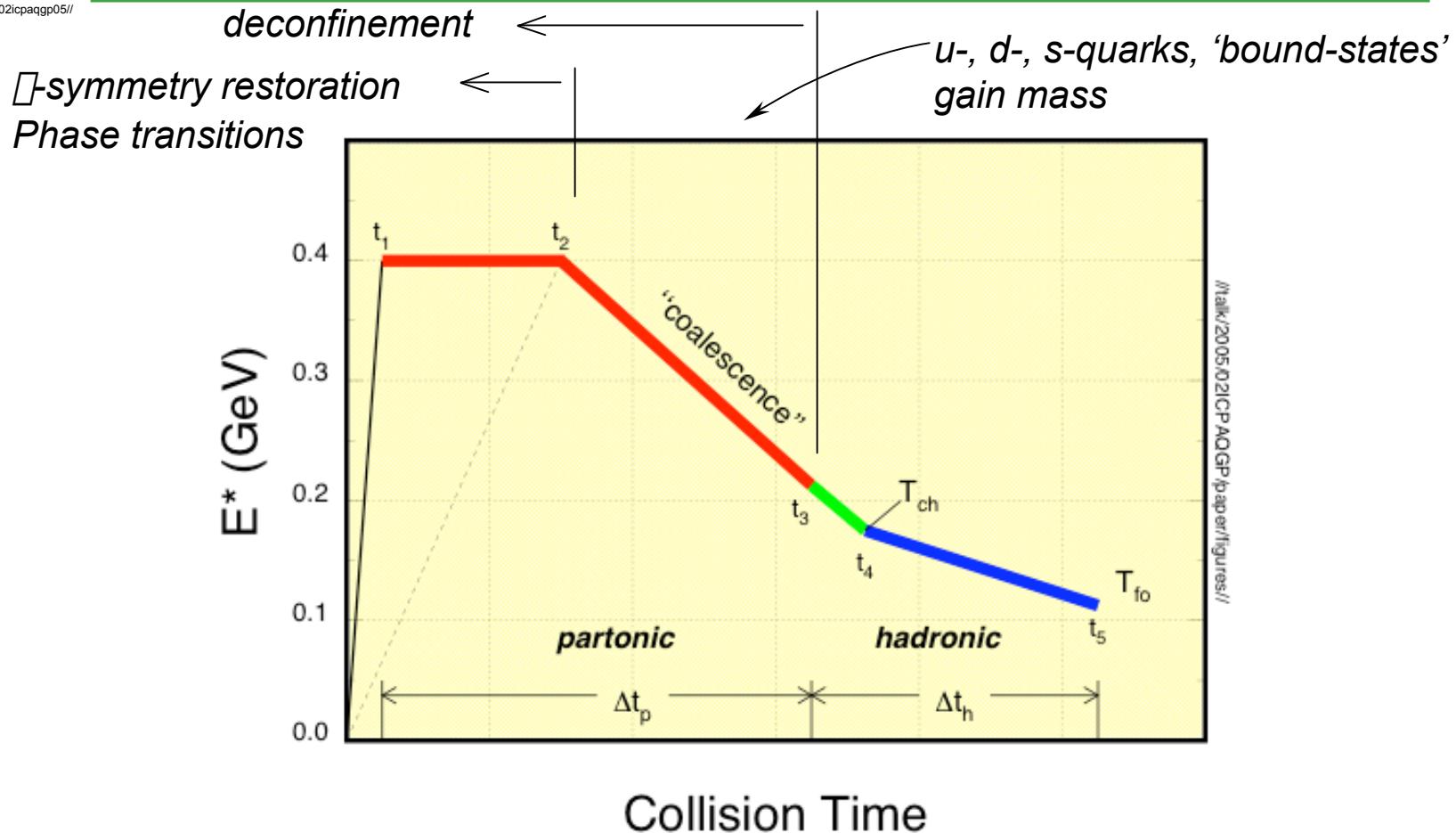
**Multi-strange hadrons  $\Xi$  and  $\Omega$  flow!**

4)\*\*\* Number of quark scaling:

**Partonic ( $u,d,s$ ) collectivity  
deconfinement at RHIC**



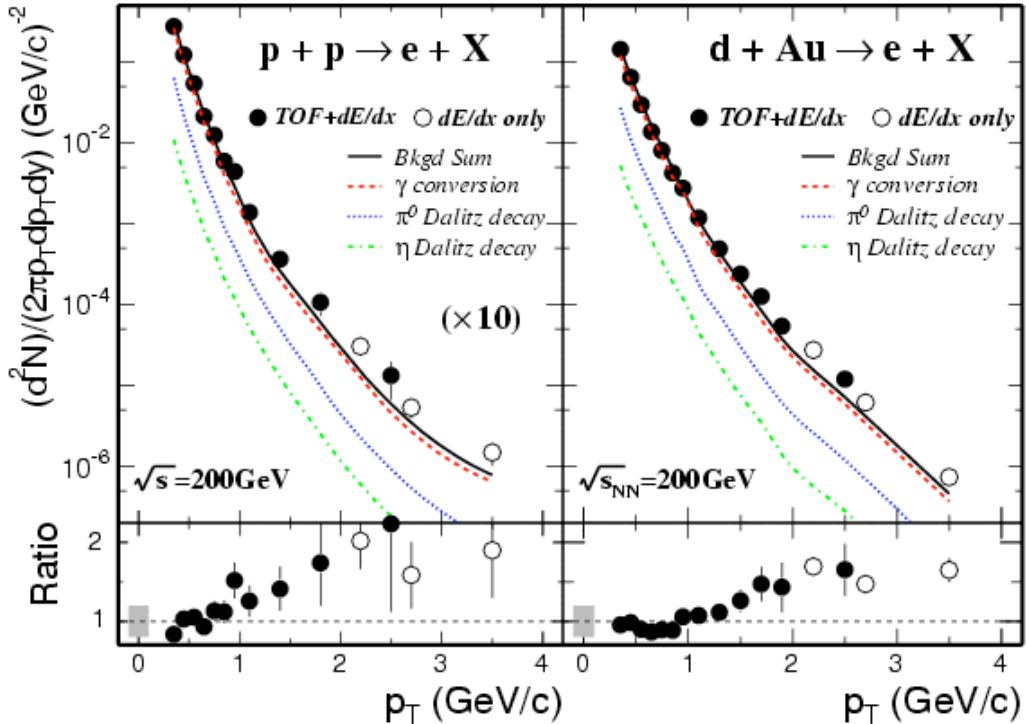
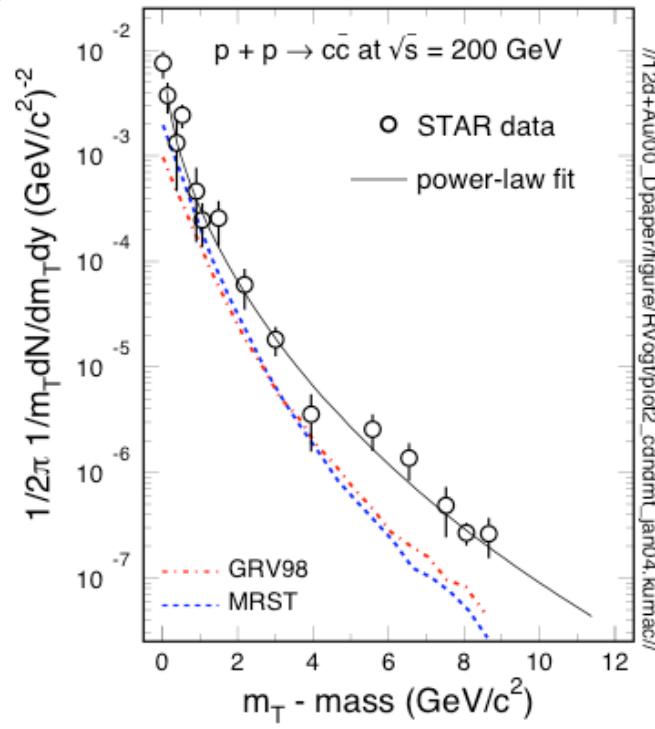
# Time scale and coalescence



- 1) Coalescence processes occur during phase transition and hadronization;
- 2) Light-quarks and ‘bound-states’ gain mass accompanied by expansion;
- 3) Early thermalization with partons and its duration need to be checked.

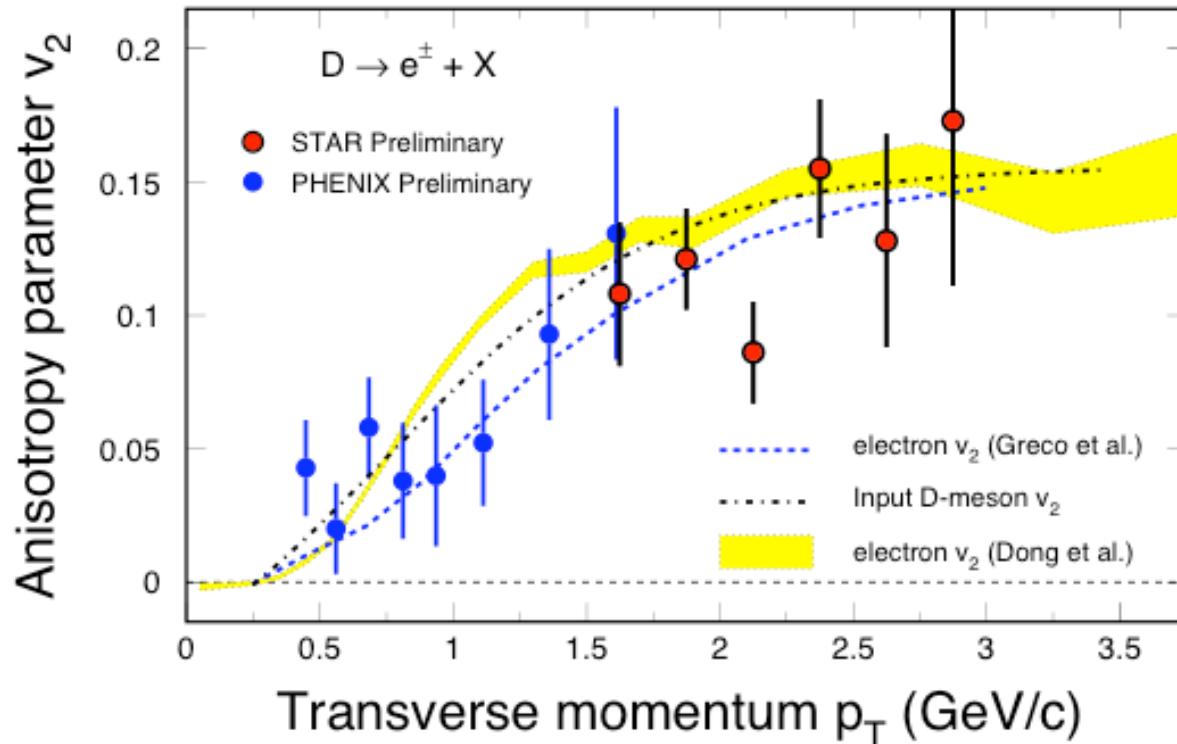


# Open charm production at RHIC



- First reconstructed open charm spectrum at RHIC
  - STAR data: *Phys. Rev. Lett.*, *in print*; *nucl-ex/0406007*, *nucl-ex/0404029*
  - pQCD  $p_T$ -spectra are steeper,  $\square_{\text{total}}$  is smaller by a factor of 3-5
  - model results:  $\square_{cc}^{\text{total}} \sim 1400$  (b)
- R. Vogt, 2004*

# Non-photonic electron $v_2$



STAR: 0-80% (F.Laue SQM04)  
 statistical error,  $\square$  decay correction  
 F. Laue et al. nucl-ex/0411007

V. Greco, C. M. Ko, R. Rapp, Phys.Lett. **B595**, 202(2004).  
 X. Dong, S. Esumi, et al., Phys. Lett. **B597**, 328(2004).  
 E. Bratkovskaya et al., Phys. Rev. C, in print; (hep-ph/0409047).

PHENIX: Minimum bias  
 M. Kaneta et al, J.Phys. **G30**, S1217(04)  
 PHENIX: nucl-ex/0502009

- coalescence process
- NQ-scaling
- Hadronic interactions,  $D^*$

# Summary & Outlook

(1) Collectivity - pressure gradient  $\partial P_{QCD}$

- ⇒ **Deconfinement**
- ⇒ **Partonic collectivity**

(2) Partonic (light flavors:*u,d,s*) thermalization

- heavy flavor  $v_2$  and spectra
- di-lepton and thermal photon spectra
- $J/\psi$  production

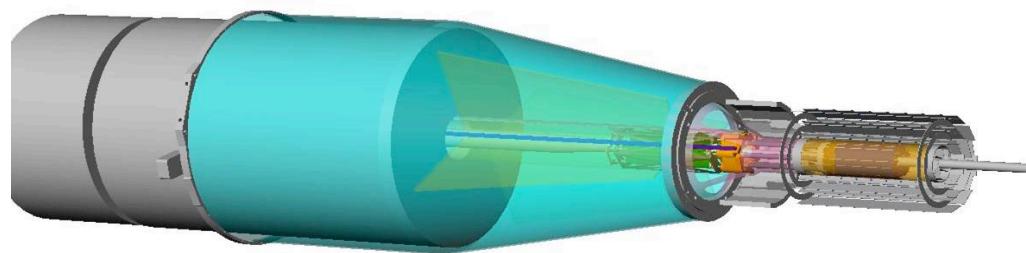
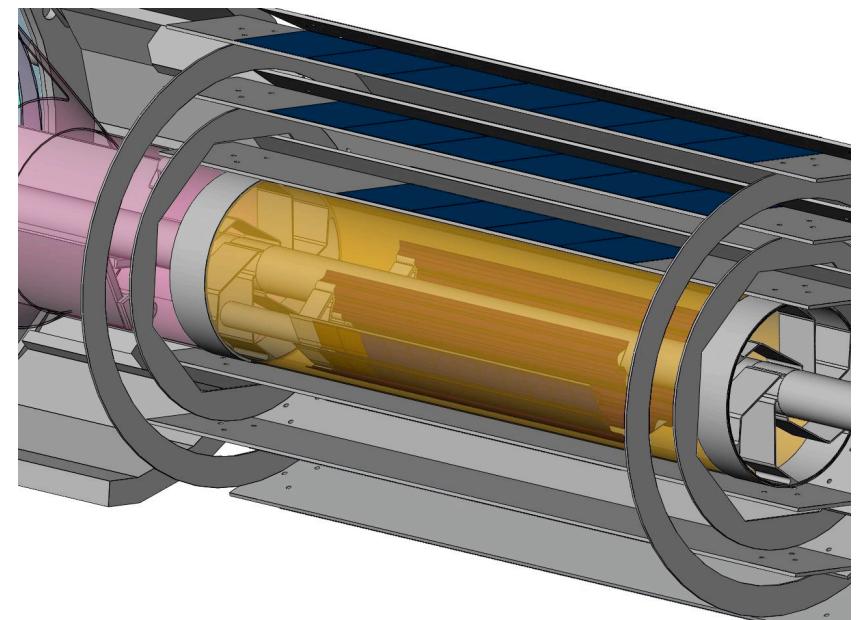
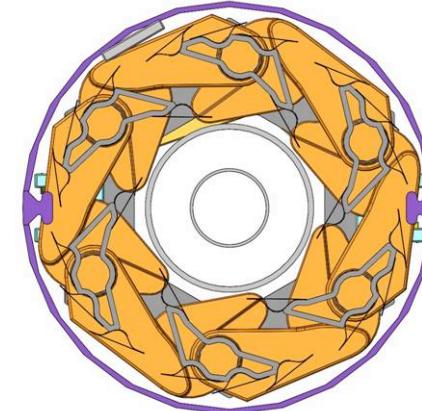
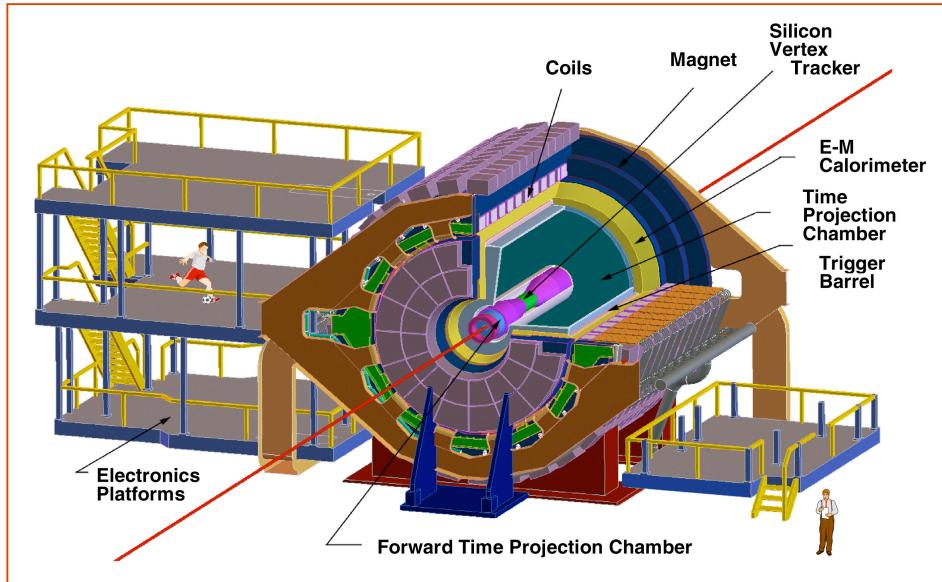
(3)  $\psi$ -vertex upgrades Phenix and STAR

- open charm and beauty
- resonances with both hadronic & leptonic decays



//Talk/2005/02icpaqgp05//

# STAR $\ell$ -vertex detector



J. Thomas, H. Wieman et al., STAR Collaboration